Final Results of Advanced Cryo-Tanks Research Project CHATT

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The EU-FP7-funded study called CHATT (Cryogenic Hypersonic Advanced Tank Technologies) has been initiated early 2012 and will successfully be finished in June 2015. One of its core objectives is to investigate Carbon Fiber Reinforced Plastic (CFRP) cryogenic pressure tanks. The focus of the paper is on the technology development tasks of the study and its major obtained results including manufacturing and testing of four subscale tanks.

The paper outlines the study logic of CHATT, gives a presentation of the technology development tasks, and summarizes major research results obtained until project completion. Finally, potential next steps in follow-on technology development and maturation are discussed.

Abbreviations

CAD	Computer Aided Design
CFD	Computational Fluid Dynamics
CFRP	Carbon Fibre Reinforced Plastic
CTE	Coefficient of Thermal Expansion
FEA	Finite Element Analysis
FEM	Finite Element Method
LH2	Liquid Hydrogen
LOX	Liquid Oxygen
SME	Small Medium Enterprise
TPS	Thermal Protection System
TRL	Technology Readiness Level
-C	cementable

1 Introduction

In future aviation and particularly in hypersonic systems new propellants will be used, such as liquid hydrogen, liquid methane and possibly liquid oxygen. EU funded studies in Europe such as FAST20XX, ATLLAS or LAPCAT investigate(d) advanced vehicles with these fuels for passenger transport like the SpaceLiner or Lapcat A2 and some of their constituent materials and associated propulsion challenges. The question of cryogenic propellant storage inside an airliner – although of critical importance but by far not yet mastered – has not been addressed in comparable detail until the start of the CHATT project.

The need for more detailed investigations on liquid hydrogen or methane tanks in future airliners is not only urgent in future hypersonic aeronautics, but is also essential for environmental reasons in subsonic aviation. Liquid hydrogen, produced on the basis of renewable energy, is the only known new fuel meeting the requirements. Cryogenic fuel propulsion is already operational in advanced launcher systems and Europe has some expertise with the Ariane rocket. However, the airliner systems will require more complex technology (compared to those existing in today's launchers), such as ultra-light-weight and reusable propellant tank systems. The propellant tank technologies are critical for the vehicle operations, cost and safety.

New materials and design concepts are required, such as fibre based composite materials, in order to reduce the tank weight and to increase the structural performance. This is particularly important if the tank has load carrying functions. Different to current rocket launch systems, the durability through hundreds or even thousands of flight cycles must be assured. Tank liners are another essential element of a tank design in order to assure the material compatibility over long durations.

2 Organizational structure

The project CHATT is part of the European Commission's Seventh Framework Programme (FP7) and run on behalf of the Commission by DLR-SART in a multinational collaboration. One of the core objectives is to investigate Carbon Fiber Reinforced Plastic (CFRP) cryogenic pressure tanks. Four different subscale CFRP-tanks are designed, manufactured, and tested. The total budget is exceeding 4.2 M€ with an EU contribution of almost 3.3 M€ [1]. The project started in January 2012, run for 42 months and now ends on 30th June 2015 as planned.

Eleven different partners from seven European countries are participating in CHATT. A list of all involved partners with their country of origin and full organization name is presented in Table 1.

Table 1: List of CHATT partners

Short Name	Country	Participant organization name
DLR	Germany	Deutsches Zentrum für Luft- und Raumfahrt
FOI	Sweden	Totalförsvarets Forskningsinstitut
SICOMP	Sweden	Swerea SICOMP
ULB	Belgium	Université Libre de Bruxelles
ORB	Austria	Orbspace
ELTE	Hungary	Loránd Eötvös University (ELTE) Budapest
TUD	Netherlands	Technical University Delft
ECM	Germany	Engineered Ceramic Materials GmbH
CENAERO	Belgium	Centre de Recherche en Aéronautique ASBL
GDL	UK	Gas-Dynamics Limited
ALE	Netherlands	Advanced Lightweight Engineering

The organizational breakdown of the CHATT project is very balanced concerning the type of the partners and is as follows:

- SME: 5 (ORB, ECM, CENAERO, GDL, ALE)
- Research institutes: 3 (DLR, FOI, SICOMP)
- Universities: 3 (ULB, ELTE, TUD)

Large industrial companies are not involved in CHATT. All partners receive a 75 % funding by the EU-commission for their research activities. 25 % are funded by internal contribution of each partner.

The project is managed by DLR-SART with the support of Work-Package leaders based in partner organizations. Regular meetings are essential for the technical exchange. A total of 6 progress meeting (PM) had been organized every 6-8 months including a Mid-Term Review (MTR) and the Final Presentation. The PMs were held in Budapest, Piteå (Sweden), Braunschweig, Brussels (including MTR), Delft, and the Final Presentation at DLR in Bremen. Other meetings or reviews on WP level have been organized when necessary.

A dedicated public internet site featuring general information about CHATT as well as providing published papers for download is available at http://www.chatt.aero .

3 Research activities

The research performed in CHATT has increased the knowledge within Europe to a practical cryogenic tank demonstrator level for future aerospace reusable lightweight composite cryogenic structures. The advantages and disadvantages of using liner/linerless tank designs has been investigated as well as issues related to the realization of more complex geometrical tank shapes.

The project is broken down into three main technical activities (Workpackages WP2 to WP4), which have a close interaction as shown in Figure 1.

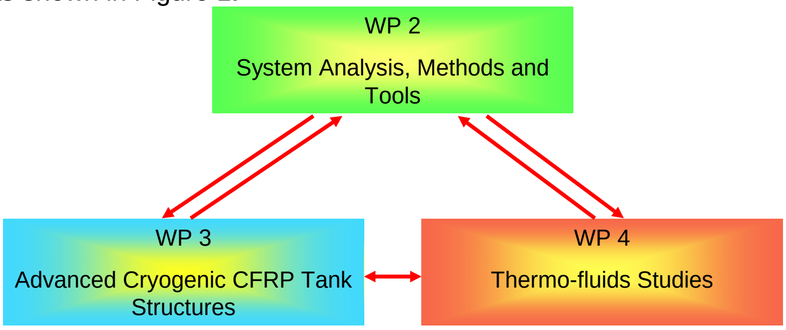

Figure 1: Interaction of different workpackages in CHATT study [1]

A central, steering role is applied to WP2 focusing on system requirements of advanced passenger airplanes, the development, test and implementation of engineering methods and tools. The two remaining workpackages WP3 and WP4 are dedicated to fundamental research with special focus on manufacturing and testing of fully integrated subscale hardware samples. Both WPs are serving as modules supporting the vehicle design and the verification of fast engineering methods.

Four different subscale CFRP-tanks are designed, manufactured, and tested under mechanical and thermal loads within the scope of the CHATT project. The challenge in developing a cryogenic CFRP tank is finding a solution for the problems caused by differences in thermal expansion coefficients (CTE) on a microscopic scale. If a liner is required, there is also the challenge to overcome the differences in CTE of the liner with respect to the structural shell.

All advanced cryogenic tank technologies investigated within CHATT are driven by system demands of future hypersonic passenger configurations. Such vehicles have been under study in other EU-funded cooperative projects LAPCAT and FAST20XX: LAPCAT A2, LAPCAT M8, and the SpaceLiner. Thus, the vehicles have already reached a certain level of maturity in their respective propulsion demands and overall size. However, the cryogenic tank systems have not been studied previously in Europe in any detail and major challenges concerning tank weight, sloshing, and insulation have not been addressed much prior to the start of the CHATT project.

One supersonic transport aircraft being researched as part of CHATT is the A2 Mach 5 Civil Transport of Reaction Engines Limited (Figure 2). This aircraft design should be capable of flying from Europe to Australia in 5 hours carrying 300 passengers. The vehicle is intended to have about 20000 kilometers range calling for the use of liquid hydrogen as a fuel which also can be used to cool the vehicle and the air entering the engines via a precooler.

Figure 2: LAPCAT A2 hypersonic Mach 5 Civil Transport in artist's impression [2]

An interesting alternative to air-breathing hypersonic passenger airliners in the field of future high-speed intercontinental passenger transport vehicles might be a rocket-propelled, suborbital craft. Such a new kind of 'space tourism' based on a two stage RLV has been proposed by DLR under the name SpaceLiner [3]. Ultra long-haul distances like Europe – Australia could be flown in 90 minutes. Another interesting intercontinental destination between Europe and North-West America could be reduced to flight times of about one hour. The SpaceLiner 7 configuration reached after several evolutionary steps is shown in Figure 3. The propellant crossfeed between the two rocket-powered stages of the SpaceLiner operating in parallel during the early flight phase enables a significant performance improvement. However, crossfeed between operational stages is highly innovative and has never been demonstrated in flight. A simulation of the steady and transient behavior in the propellant feed-system has been performed along the powered flight and its preliminary design has been defined [5, 7] in CHATT. The positions of the external feedlines on top of the booster stage are visible in Figure 3 on the right.

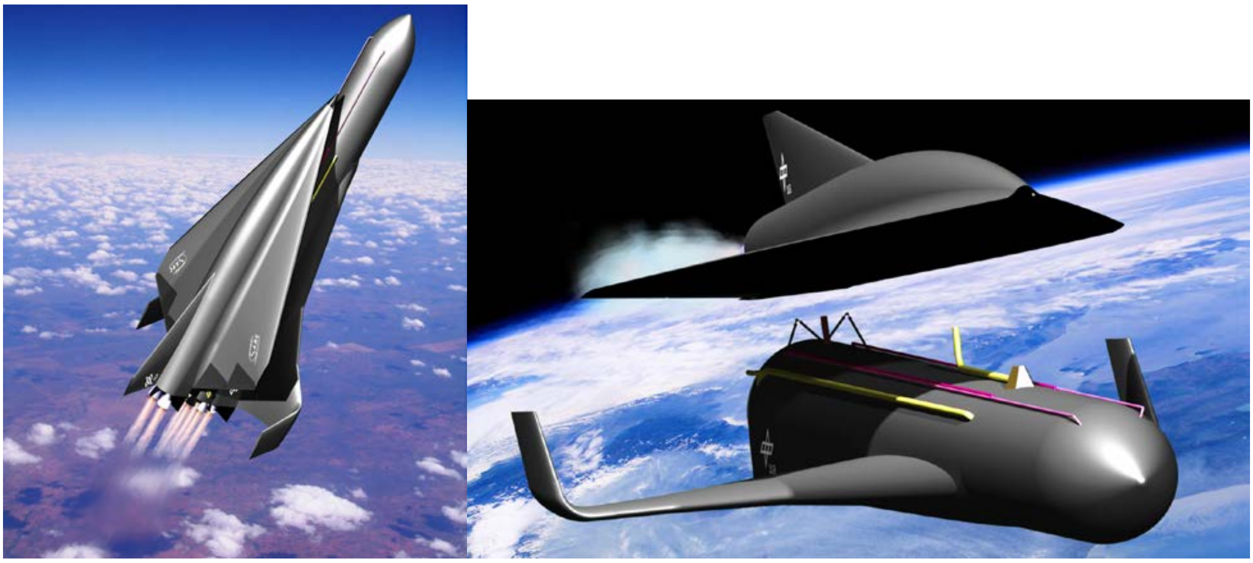

Figure 3: SpaceLiner 7 hypersonic passenger transport in artist's impressions during vertical ascent and at staging

Propellant management is imperative to achieve reliable and efficient vehicle operation. It is therefore the third pillar of the CHATT study and covers tank pressurization, fuel location/retention, and sloshing in horizontal tanks. Apart from thermal aspects, sloshing of cryogenic fluids within the tanks can have a significant impact on its center of gravity and hence its controllability is put into question. Counter-measures such as anti-sloshing devices and tank design are susceptible to reduce these effects but will come at the cost of increased mass and production effort.

Further, a ceramic heat-exchanger is investigated in CHATT as well as the air-conditioning system for the airbreathing hypersonic vehicles and aerogel tank insulation. The aerogel is an open-celled, nanoporous, solid foam which could become an attractive insulation material for cryogenic tanks in the future. Supported by CHATT, a cost efficient production process is developed for alumina cryogels by ELTE [14].

4 Composite Cryogenic Tank Investigations

Fibre reinforced composite materials are structurally most efficient for pressure vessels because there is the possibility to direct the right amount of fibers according to the orientation and the magnitude of the principal stresses, which makes it an iso-tensoid structure. Carbon fibers are currently known to have the highest combination of specific strength and stiffness [4, 14]. However, some specific challenges remain with large scale cryogenic tanks of relatively low internal pressure which usually require a (potentially metallic) liner and hence face difficulties beating the optimized metallic launcher tank structures.

Several research programs in the US have fabricated and tested composite LH2 tanks including DC-XA (circa 1994), X-33 (c. 1999) and the Space Launch Initiative (SLI) Composite Cryotank Program (c. 2006) [13]. The X-33 demonstrator tank consisted of a multilobed and linerless configuration with integrally bonded, woven composite joints. However, that tank failed in 1999 during ground testing due to polymer matrix micro-cracking and leakage into the sandwich core material causing delamination between the core and the inner composite skin. The tank showed leakage with subsequent damage, so-called "cryopumping".

Northrop Grumman and NASA later completed within the NGLT project a nine-month test series to demonstrate a cylindrical composite cryogenic tank. The problems that brought the X-33 to a halt were proven to be solved in 40 load cycles performed without failure. The integral tank, utilizing an impermeable barrier film between the inner tank wall and the honeycomb [4] was filled with LH2 and pressurized.

NASA's goal of the recent Composite Cryotank Technology Demonstration (CCTD) Project is to design and build a composite liquid-hydrogen cryogenic tank that can save 30% in weight and 25% in cost compared to state-of-the-art aluminum metallic cryogenic tank technology [13]. The loads, length, and volume were based on a 10 m diameter Ares V launcher Earth Departure (upper) Stage (EDS) LH2 tank. The

NASA team developed a metallic aluminum alloy cryotank concept for comparison to three industry IM7/977-2 composite concepts with the same overall dimensions: Boeing fluted core, Lockheed-Martin externally stiffened, and Northrop Grumman sandwich. All three composite concepts exceeded the 30% weight reductions desired by the CCTD Project when compared to the metallic cryotank [13].

NASA has selected a 5.5-m diameter demonstrator test tank in CCTD Phase II which has been manufactured by Boeing. This tank is linerless and is using thin-plies for permeation barrier, ventable and purgeable sandwich structures, and structural Health Monitoring to support damage tolerance [8]. After initial successful completion of a 2.4 m precursor test article [8, 9], this tank has been built around a 5 m segmented tool mandrel and subsequently been tested in 2014 at NASA MSFC. The Boeing-built tank passed a series of fill-and-drain tests, containing cryogenic liquid hydrogen with acceptable seepage [10]. Weight savings over aluminum approached the 35% target set by NASA [10].

4.1 CFRP demonstrator tank structures in CHATT

After the CHATT-study passing its mid-term milestone, hardware manufacturing is almost completed and several tests of the subscale hardware have been performed. The following sections give an overview on the work focused on the CFRP tank studies of WP3.

Four different subscale demonstrator tanks have been designed, have been manufactured and are tested within CHATT:

- Cylindrical tank with liner by DLR
- Cylindrical tank without liner by FOI/SICOMP
- Complex shape tank with liner by TU Delft
- Dry wound cylindrical tank with liner by ALE

In the first step, an overview on CFRP tanks' state-of-the-art has been jointly collected [12]. Within CHATT several liner materials have been identified as potential polymer candidates for evaluation. It is essential that these materials have a large strain to failure at cryogenic temperature and it is necessary to match their CTE to the laminate to decrease thermal stresses. The work conducted in CHATT contained a study of the dependency of mechanical properties of the liner materials on temperatures relevant for cryogenic fuel tank applications. In CHATT also liner materials have been studied which were adhesively bonded to a base laminate in order to evaluate the performance of different liner candidates in contact with damage in the CFRP tank wall. Results on the liner investigations have been published in [18, 19].

4.2 Design of Cylindrical Tanks with Liner

4.2.1 Cylindrical tank with liner (DLR)

A cylindrical tank was manufactured by filament-winding at DLR in Braunschweig. Tank design follows the CFRP-net geometry. The tank is about 3 m in length with a cylindrical length of 2.4 m and a diameter of 1 m. It has a total volume of 1.9 m³ and its design is according to Figure 4.

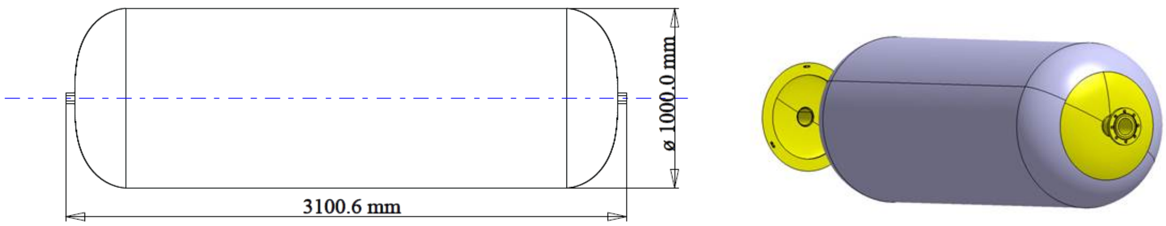

Figure 4: Schematic description of the geometry of the DLR CFRP demonstrator tank (left), Assembly design of the liner with metal-domes (right)

In particular, a combination of glass fibers and CFRP was applied, whereas the CFRP was used for a second winding with larger outer diameter on top of the glass layers. Table 2 clarifies the layup scheme. The tank was manufactured with wet winding on a PE-liner. The Epoxy resin from Huntsman Araldite® LY 564 (low viscosity epoxy resin) with Aradur® 22962 (cycloaliphatic polyamine) was used. The first layer is a helix glass layer with an angle of 6.8°.

Examples from the winding process at DLR Braunschweig are shown in Figure 5 and Figure 6. The final layer is a second CFRP hoop layer visible on the right. The finished tank is finally wrapped with a peel ply (Figure 6). Through the peel ply the excess resin is removed.

Table 2: Parameters used in the manufacturing of the DLR CFRP tank demonstrator

model	Type	layer	orientation	position	remarks
Helix winding	glass	1/2	+/- 6.8°	Complete tank	2400tex
Hoop winding	glass	3/4	0°	Cylindrical area	2400tex
Hoop winding	CFRP	5/6	0°	Cylindrical area	2400tex
Helix winding	CFRP	7/8	+/- 41.5°	Complete tank	2400tex
Hoop winding	CFRP	9/10	0°	Cylindrical area	2400tex

Figure 5: Winding of the helix CFRP layer (left) and final CFRP hoop layer (right)


Figure 6: Wrapping of the peel ply

Curing in the autoclave is the normal curing cycle for the resin. The autoclave curing process finalized the tank manufacturing. The resin is slightly gray (Figure 7). This is the result of small micropores caused by the impregnation of the fiber material from the foam roller.


Figure 7: Finished CFRP demonstrator tank after curing in autoclave

The large cylindrical CFRP-tank has been delivered in May 2014 to the cryogenic laboratory at DLR Bremen for further testing. Fill- and drain procedures using water have been run since and leakage under pressurized conditions is found to be small. Meanwhile the sloshing and related fluid damping behavior has been tested on a hexapod table using water and is compared with CFD simulations [11].

4.2.2 Cylindrical tank with liner (ALE)

Beyond the wet-wound tanks, a dry filament wound cryogenic cylindrical demonstrator tank has been designed, produced by ALE and is under testing. The main risk of using a dry filament wound tank in cryogenic environment is that in unpressurized state the fibers could separate from the liner due to the difference in their CTE and start to relocate. This tank has a cylindrical mid-section with two isotensoid shaped ends. The tank has an approximate length of 0.57 m, a diameter of 0.29 m, and a volume of 33 l.

ALE has developed in-house software called PresVes which is able to simulate fiber circuits and fiber patterns according the netting theory and is written in Matlab. PresVes is able to export machine code for the tumble winder at ALE. Furthermore, the fiber network can be exported as a truss element mesh in order to perform FEA.

The liner has a cylindrical mid-section with isotensoid domes; see Figure 8 for global dimensions. The outer contour of the liner is determined using PresVes. The produced wall thickness is around 2 mm and has been determined iteratively using FEA. The length over diameter ratio is L/D = 2. Liners are produced using the blow moulding process. Therefore, the material selected for the liner is PE because the previously foreseen Vectra LCP grade A435 [18, 19] is not suitable for blow moulding. Unfortunately, however, the CTE of PE is no longer favorable in combination with the T700 fibers due to its high value. The approximate liner mass is 0.38 kg.

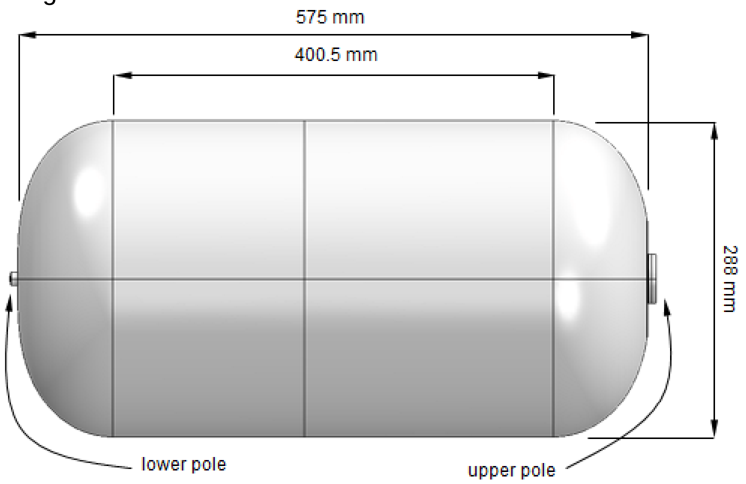

Figure 8: Liner dimensions for dry-wound tank

FEM analyses of the dry wound tank have been performed to evaluate the following aspects:

- Deformations caused by cool down from room temperature to LH2 temperature
- Burst pressure validation by failure analysis of the fiber network, the liner and the closure parts at LH2 temperature

The maximum fiber strain that occurs at 12 bar internal pressure (burst pressure requirement) and at LH2 temperature is 0.13% (Figure 9). This strain magnitude is below the allowable strain of T700. With a calculated safety factor of 1.03% / 0.13% ≈ 7.9 it is concluded that the fiber network meets the load requirements.

The function of the dry carbon fiber layup is to carry the load due to the internal tank pressure. The liner and all overlying layers are assumed as non-load sharing. Toray T700 24k untwisted rovings are selected. Two different winding layers are placed in the following order:

1. Helix layer; which is a fully wrapped layer that covers the liner completely. Two T700 24k rovings are placed in 63 circuits with 8 segments filled with 8 bundles. The mass of the fibers in this layer is estimated at 0.653 kg.
2. Hoop layer; which covers the cylindrical part of the liner. The hoop layer covers the helix layer and has 108 circuits. The mass of these fibers is approximately 0.325 kg.

The dome closure consists of an aluminum insert and an aluminum counterpart. The insert is installed onto the liner by a snap connection.

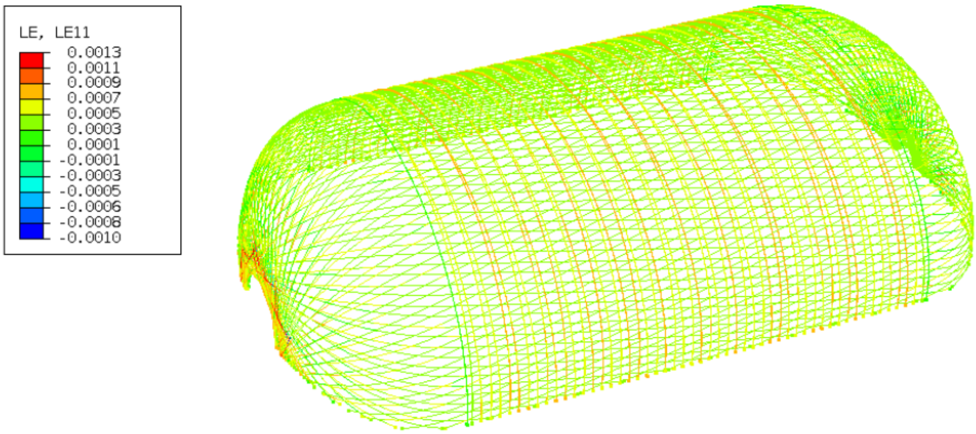

Figure 9: Strain at 12 bar and at LH2 temperature in half of the fiber network [16]

Winding of the helix layer and winding of the hoop layer at the ALE workshop are visible in Figure 10. Taped fiber ends and a transparent foil prevent fiber movement. A total of three tanks have been produced by ALE. The production state after winding is shown in Figure 11.

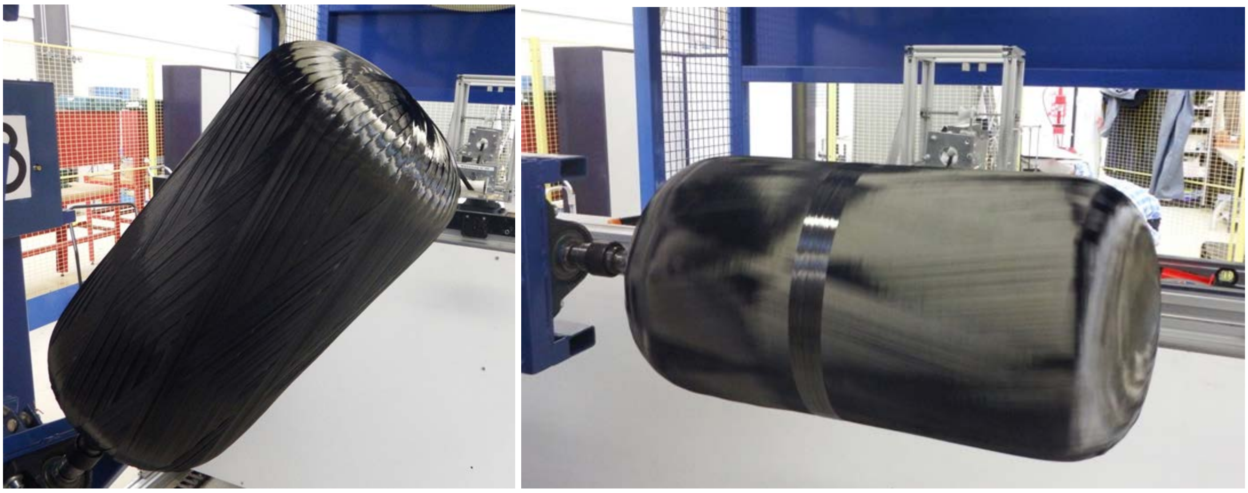

Figure 10: Winding of helix layer (left) and winding of hoop layer (right) at ALE

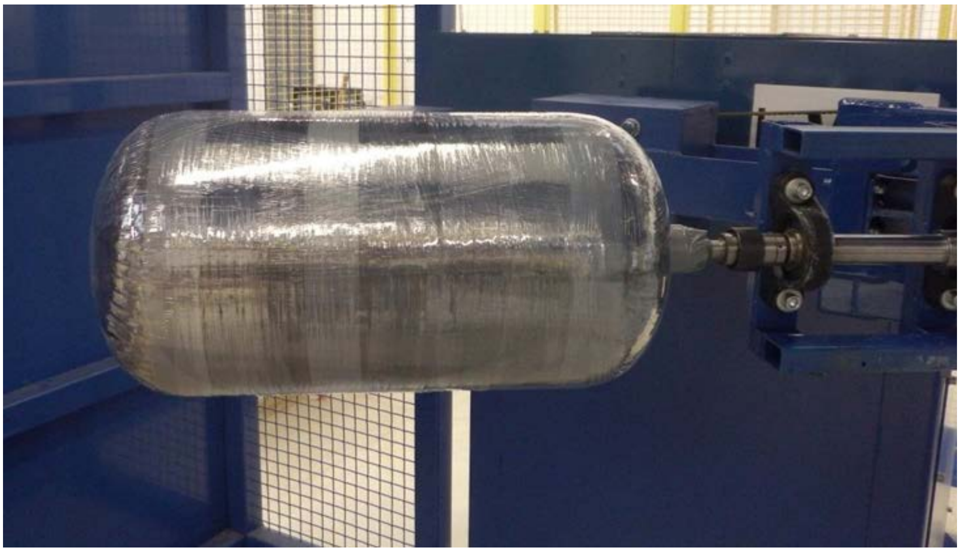

Figure 11: Demonstrator tank of ALE after winding with protection foil

The tank has been subject to pressurization tests at ALE and subsequently was delivered to the DLR cry-olab in Bremen. Fill and drain tests using liquid nitrogen have been performed including a sequence of several pressurization and venting cycles.

4.3 Design of Cylindrical Tanks without Liner (Swerea SICOMP, FOI)

Actually, the linerless tank demonstrators built in Sweden are not closed volume tanks but rather tubes with a cylindrical section and open ends. The reason for choosing the tube configuration is the ability to validate the design by easy testing in the relevant loading conditions internal pressure, low temperatures and axial load. The manufacturing of the tube demonstrator tank is performed at Swerea SICOMP while the testing is executed at FOI. The linerless demonstrator tank concept is based on the utilization of thin-ply laminates and the superior mechanical properties these novel materials show. Both, all thin-ply tank concepts and hybrid concepts are evaluated. Several subscale demonstrator tubes were manufactured by filament winding on a steel mandrel with an external diameter of 165 mm to verify the results and test various concepts.

Numerous processing methods have been studied including one and two step winding and curing, variable winding tension, induction heating and shrink tape. However, most of the studied combinations of traditional material- and process parameters have a small effect on the operational stress state in the tank. The intended step-change in material performance was instead reached by utilizing a novel spread-tow material from the Swedish Oxeon company named TeXtreme®. As laminate material the Carbon Fiber Spread Tow TeXtreme® 50 UD TR50S WO /20:50, unidirectional, at 50 μm ply thickness has been used. Spread tow is a relatively new material and has a huge potential for performance improvements in many applications.

Finite Element analysis was used for various demonstrator cases, such as hybrid laminates (traditional and thin-ply composites) as well as pure thin-ply composites (only using TeXtreme®), to find the optimum lay-up of the demonstrator tubes considering both the real load case as well as the selected test conditions used at FOI for testing of the demonstrator tubes. Mechanical testing on specimen level performed at Swerea SICOMP also show that the critical transverse micro-crack initiation stress increases approximately from 60 to 120 MPa depending on the ply thickness

The TeXtreme® material had never been used for wet filament winding before the CHATT project started. Initial test tubes were hence manufactured by Swerea SICOMP to verify the quality of the laminates. The selected winding angle was 89.8º (tangential) with 2 mm laminate thickness. The void content in the manufactured samples were measured and found at 5%, which is unacceptably high. The problem was traced to the poor processability regarding permeability in the thickness direction.

This manufacturing problem was solved by introducing an innovative solution called HOMS (HOles, Momentary or Stationary) in the spread tow weave to facilitate impregnation [20]. The idea is to temporarily push the carbon fibers sideways in a gentle manner without damaging the fibers during manufacturing. Additional test tubes with the new method were manufactured by SICOMP using the same process parameters, lay-up and thickness as the previous test tubes including the HOMS procedure. The void content in the manufactured samples were measured and the void content was approximately 0 %, which is considered high quality manufacturing (see Figure 12).

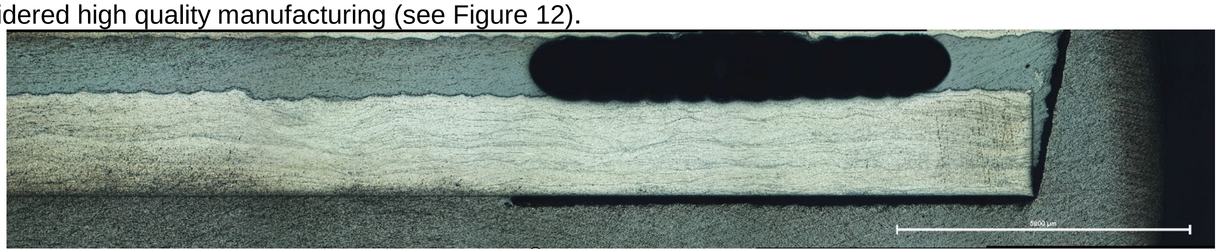

Figure 12: 2 mm thick TeXtreme® carbon/epoxy laminate with 0 % void content

Several tubes with different fibre architecture, different laminate thickness and orientation were manufactured. Some of the tubes were produced with the primary objective of optimizing the manufacturing procedure and some of them for testing at FOI in terms of performance as demonstrator tanks.

Manufacturing of the final optimized hybrid demonstrator casing is shown in Figure 13. Four layers of T700 have been wound at ±45° and 20 layers of TeXtreme® at ±25°. The tube's ends are wound with glass fiber at 90° to serve as tabs for testing. An internal view of the finished demonstrator tube is shown in Figure 14.

The optimization of the lay-up and material in the final demonstrator tube was performed for the specific load case used at FOI: -150°C, an inner pressure of 3 bar and increasing the axial load until failure. Helium gas was used for tracing the leak rate throughout the test together with strain gauges to measure the strain at critical locations in the demonstrator. The test setup is shown in Figure 15.

Figure 13: Tube manufacturing with ±45° layer of T700 (left), ±25° layer of TeXtreme® (right)

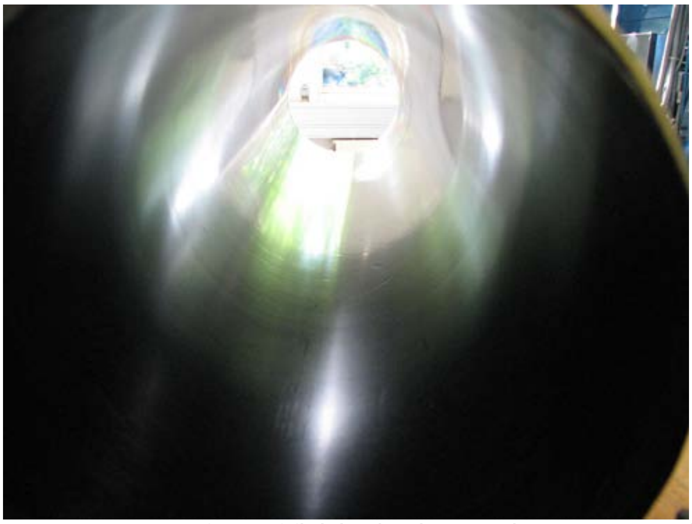

Figure 14: Inner surface of finished subscale demonstrator tube

Figure 15: Test set-up used at FOI for validation of the demonstrator tank performance

The results of the mechanical testing performed at FOI validated the desired performance of the design configuration used for the linerless tank concept. The axial load reached 998 kN which corresponds to an axial strain of 1.6% before failure and subsequent leakage through the tank wall was detected.

4.4 Design of Cryogenic Tanks with Complex Shape (TUD)

Tanks with a more complex shape then cylinders and spheres offer the potential of an improved volumetric efficiency inside the fuselage or wing of hypersonic vehicles. A relatively simple structure has been selected for the CHATT scaled prototype of a multibubble tank to be built at TU Delft which, however, contains all the specific design and manufacturing issues of such a complicated spheres arrangement. It has been decided to design, evaluate and produce a planar arrangement of identical spheres with double symmetry. The radii of the four bubbles of the intended prototype are all at the same 150 mm. The distance between the centers of the incomplete spheres is equal to $R\sqrt{2}$.

Mechanical and thermal loads are derived of the SpaceLiner passenger stage LH2-tank. These are representative of hypersonic applications although a multibubble tank is unlikely to be selected in the SpaceLiner for carrying cryogenic fluids. However, water of the active cooling system could be stored very efficiently inside the available volume of the wing root using this special tank shape. Two external ports - with a circular cross section- are designed at the two front ends of the sub-scale tank. These ports will be used for filling and draining of the tank prior and post to operation. The external ports are reinforced by metal bosses, in order not to significantly thicken the shell. An internal structural web was designed at the sub-scale tank, thus dividing it into two chambers. The use of an internal structural web provides a structural support at the intersection. Holes were designed at the structural web, in order to create communication ports allowing liquid to move between sections and evenly distribute the pressure within the vessel. A reinforcing pad is created adjacent to the opening in order to reduce stress concentrations created near the hole. The design in CATIA is presented in Figure 16.

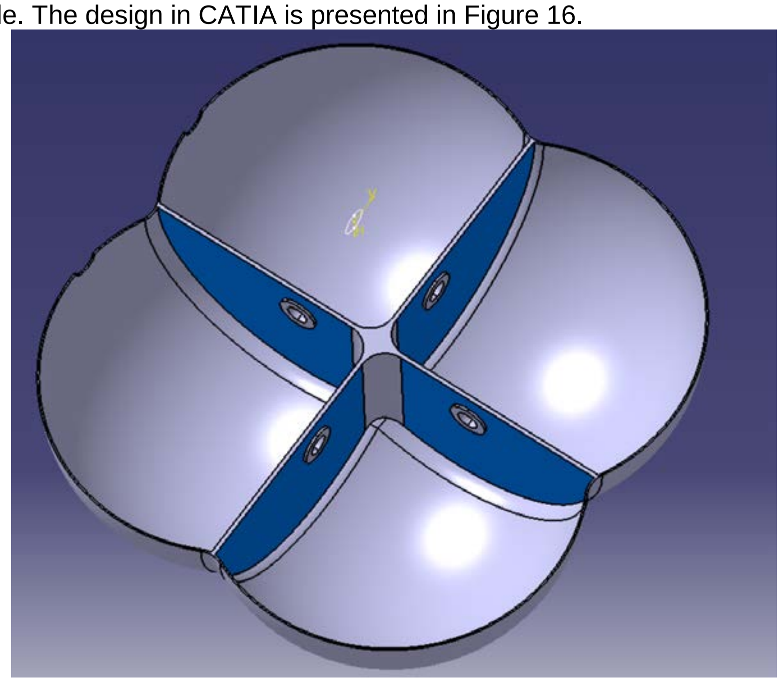

Figure 16: Arrangement of four identical intersecting spheres possessing double symmetry lay-up and external reinforcement of the multi bubble design

The second subscale tank configuration analyzed was a composite overwrapped subscale tank with a hoop fiber reinforcing the intersections and thus providing structural support. An external UD carbon tow (roving) is applied over the tank wall from the outside to the inside under tension, thus forming a ∞-sign (Figure 17). Each hoop fiber-wrapping cycle starts from the top section of the tank at the junction intersection and continues to the central hollow tube covering all unreinforced junctions at longitudinal and circumferential directions. Additionally, the area where the four intersections meet and the circular tube starts should have high radius of curvature, since the entrapped hoop fibers should be stretched against the tank wall surface. This way it will keep the sub-scale tank compact and provide support without adding extra weight to the tank. As a result the concept of having reinforcement webs at the liner and adding extra weight at the tank can be potentially dropped and thus maximizing the structural efficiency of the sub-scale tank by using hoop fibers. On the other hand there is a manufacturing challenge, since the fibers must be very carefully wrapped over the intersections and the tube for an effective load transfer between the laminate membrane and the tows.

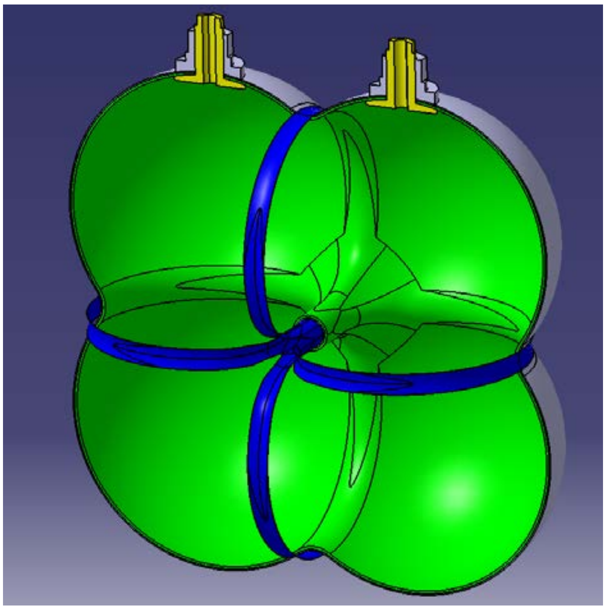

Figure 17: Intersecting spherical cells with carbon UD tows at intersections shown in blue

The POM (polyoxymethylene) liner is planned to be made in a closed mould by rotation moulding and the selected tank wall material is 913C carbon/epoxy. A dynamic mechanical analysis (DMA) to evaluate the tensile modulus values of the selected liner POM material has been performed at tension mode over the temperature range -130°C up to 130°C and -130°C up to 207°C for the composite.

In a related CHATT workpackage, mixed variable optimization using two categorical variables to define the material type and bubble configuration with one continuous variable for the radius of the bubble has been carried out by Cenaero. This approach successfully found the optimum bubble configuration for the tank with the maximum structural efficiency within the prescribed constraints [21]. The chosen constraint is the inverse of the “reserve factor” which is a function of maximum Von Mises stress and tensile strength and the composite failure criterion defined by the Tsai-Wu coefficient.

The optimizer is directing toward the region of maximum structural efficiency which subsequently corresponds to the region of low inverse reserve factor, low Tsai-Wu coefficient and maximum bubble as well as material type A950. The Von Mises stresses generated in the numerical experiment 53 are plotted in Figure 18.

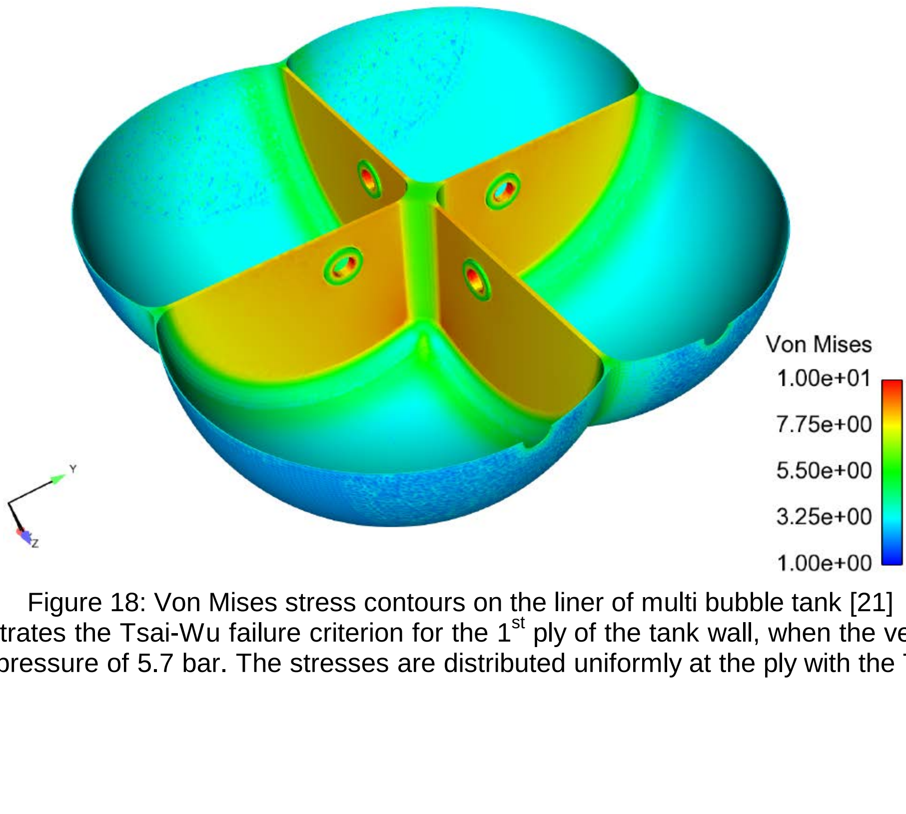

Figure 18: Von Mises stress contours on the liner of multi bubble tank [21]

Figure 19 illustrates the Tsai-Wu failure criterion for the 1st ply of the tank wall, when the vessel is subjected to internal pressure of 5.7 bar. The stresses are distributed uniformly at the ply with the Tsai-Wu values reaching a peak on the bubble intersection (of the transverse web) and the propellant feed ports. This is associated to the fact that at that intersection the ply orientation is perpendicular (at 90^{o} angle) to the local meridional force and the ply strength at transverse direction is 23 times smaller compared to the respective longitudinal direction.

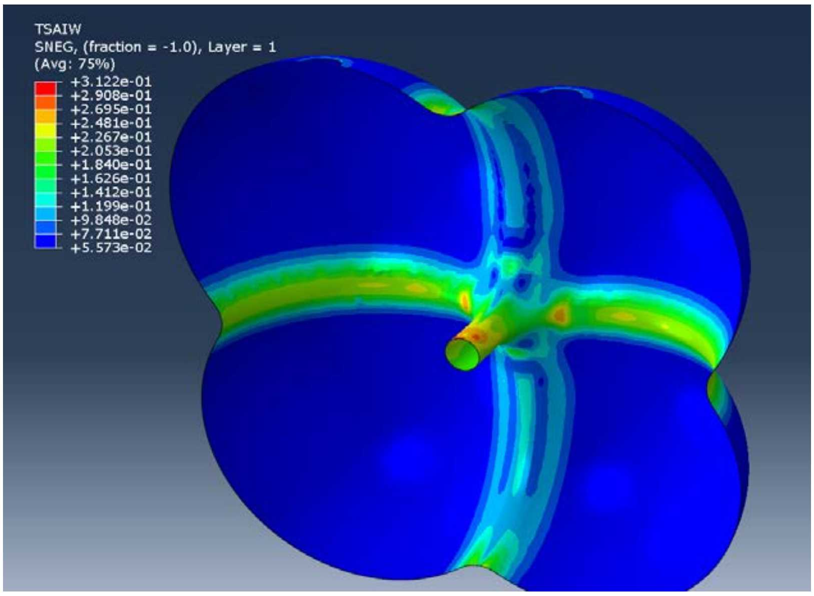

Figure 19: Tsai-Wu failure Criterion for 1st ply (0^{o}) of the tank wall.

This complex multibubble tank integrating a hoop fiber is currently under manufacturing. The liner is to be overwrapped by cross ply woven fabrics $[90/0]_s$ that are stacked under an angle of 45° with respect to each other, thus forming a quasi-isotropic laminate. In a next step the liner, which is now covered by the stacked fabrics, is packed into a bleeder foil and a vacuum foil. The toughened epoxy resin is inserted by the vacuum infusion technique. Post processing in an oven or autoclave is necessary to remove any remaining voids and ensure complete curing of the resin. In Figure 20 the aluminum mould employed for the liner manufacturing can be seen.

Figure 20: Mould of the multi bubble tank at TU Delft.

5 Conclusion

The project CHATT is part of the European Commission's Seventh Framework Programme and run by DLR-SART in a multinational collaboration. The project started in January 2012, is running for 42 months and is successfully finished as planned in June 2015. The objectives of this effort with a total budget exceeding 4.2 M€ are to investigate different CFRP cryogenic pressure tanks, propellant crossfeed systems, advanced thermal insulation materials, and ceramic heat-exchangers. Four different subscale CFRP-tanks have been designed, manufactured, and tested.

The CHATT project contributed to significant progress in the design of composite tanks for cryogenic propellant applications in Europe. Previously, the FLPP program of ESA made first steps into this technology. The different subscale demonstrators built in the project allow for a reliable assessment of promising and less-promising technologies. Polymer liners seem to be feasible for short duration applications but are sensitive to cracking. A linerless tank technology as investigated by Sicomp is promising and should be further refined, introduced into complete tanks and tested in a cryogenic propellant environment.

In future projects the lessons learned of CHATT will be useful to bring European composite tank technologies forward. Currently, the European TRL of such cryotanks is still in the range between 3 and 4 while the TRL in the US is considerably more advanced, already approaching full launcher scale dimensions with ground tests run using liquid hydrogen fuel. The next step in the development of a European composite cryotank should focus on a single, fully integrated tank demonstrator including thermal protection and some health monitoring equipment to be tested with LH2 in multiple cycles.

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